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Quasi-static Frontal Loading of the Thorax of Human Cadavers and the Hybrid III Dummy

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ABSTRACT

The purpose of this study was to determine quasistatically the stiffness and deformation of the human thorax at three sternum and three rib locations. Two unembalmed human cadavers and the Hybrid III Dummy were loaded quasi-statically in an A-P (anterior-posterior) direction on the anterior surface of the thorax at six different locations; upper, middle and lower sternum, and upper, middle, and lower right ribs (Figs. 1A & 1B). The A-P deformation of the thorax was simultaneously measured with linear pots at these rib and sternum locations during the loading. The results of these tests show: 1) using a 25.4 mm (one inch) stroke, the stiffness of the human thorax was 6 to 10 N/mm at the sternum and 3.5 to 6 N/mm at the ribs, 2) with the same stroke the stiffness of the Hybrid III was 26-44 N/mm at the sternum and 32-73 N/mm at the ribs, 3) the mid-sternum force-deflection curves for the cadaver fit a second order linear equation, and were comparable to those obtained in live subjects in a study by Tsitlik et al (1) using CPR techniques, 4) each load was repeated with the rate of loading increased from 1.7 to 102 N/mm (0.067 to 4.0 in/s), and thus far the increased loading rate has not shown consistent increase in stiffness or energy dissipation.

METHODOLOGY

The subject was mounted in a supine position in a support frame fabricated of Unistrut and aluminum plate (Fig. 2). The subject was loaded at each of six load locations with an Instron Model 1321 testing machine, in which a triaxial load cell was incorporated into the loading head. Deflection of the chest and of the loading head were measured with Novotechnik

potentiometers, model # 75, which have elastomeric damped wipers, 75 mm stroke range and 0.002 mm resolution. Loads were transferred from the Instron actuator to the subject via a 6" I beam.

Two support conditions were studied: 1) In the first, only the subject's spine was supported at the thoracic, lumbar and sacral levels. This allowed the posterior portion of the rib cage to deflect posteriorly as loads were applied anteriorly. Ribs deflection was measured on the left side only as symmetry was assumed with mid-line sternal loading (Fig. 3A). 2) In the second support condition, the subject's spine and posterior ribs were supported, loads were applied at both the sternum and the ribs, and deflections were recorded at both left and right ribs as well as the sternum. In this second support condition the posterior ribs were supported so that when the ribs were loaded, the chest would not rotate under eccentric loading (Fig. 3B). The ribs were supported continuously on gimbled plates mounted to threaded rods attached to two 51 x 51 mm (2 x 2 inch) steel box beams running parallel to and bilateral to the spine. These rib support beams were placed approximately 70 mm lateral to midline.

Table 1 shows the tests run to date.

TABLE 1

TEST NO.	TEST DATE	TEST SUBJECT	RUN NOS.	SUPPORT CONDITION
AATD1	2-22-88	HYBRID III	1-11	SPINE
AATD2	2-23-88	* CAD. #986	1-10	SPINE, RIBS
AATD3	4-01-88	HYBRID III	T1-T11, 1-15	SPINE
AATD4	4-25-88	HYBRID III	T1-T8, 1-18	SPINE, RIBS
AATD5	7-07-88	# CAD. #115	1-30	SPINE, RIBS

*CAD. #986: 29 yr old male, ht: 1.73 m, wt: 70.3 kg
#CAD. #115: 57 yr old male, ht: 1.79 m, wt: 57.6 kg

In initial tests (AATD1, AATD2), the subjects were used to evaluate the apparatus and to determine practical loading rates. After some modifications to the apparatus, the dummy and the second cadaver were then run under identical support conditions with 25.4 mm strokes applied to the sternum and ribs at loading rates of 1.7 and 102 mm/s (0.067 and 4 in/s) (AATD3, 4, and 5). Two-inch strokes were attempted but caused rib fracture and were therefore discontinued. Upper and mid-sternum stiffness data is presented for both cadaveric tests (AATD2 and AATD5). Other cadaveric stiffness and deflection data is presented for AATD5 only, as this can be directly compared to the Hybrid III data in tests AATD3 and AATD4.

RESULTS

The results of these studies indicate the following:

THORACIC STIFFNESS
(See Tables 2 and 3)

1) The human thorax is stiffer under sternal loading than under rib loading (sternum: 5.9-11.4 N/mm vs. ribs: 3.4-5.8 N/mm). The Hybrid III thorax is less stiff under sternal loading than rib loading (sternum: 26-44 N/mm vs. ribs: 32-73 N/mm). Under sternal loading, the Hybrid III dummy is approximately three to five times as stiff as the cadaver, and under rib loading, six to fourteen times as stiff.
2) Increasing the loading rate from 1.7 to 102 mm/s (a sixty-fold increase) did not consistently result in an increase in thoracic stiffness of the cadaver but did so in the dummy.
3) The loading portion of the force-deflection curve of the human cadaver could usually be fit to a second-order non-linear curve, while the Hybrid III reponse was almost linear. The cadaveric response also showed more

energy absorption. (See Figures 4A-4C). The mid-sternal, second order curve for the AATD2 and AATD5 cadavers is close to the average curve obtained by Tsitlik et al (1) in perfoming CPR on eleven live human subjects (Fig. 5).

THORACIC DEFORMATION
(See Tables 4 and 5)

1) Under sternal loading the A-P rib deflection of the human cadaver was 6 to 63% of the applied sternal stroke, while the rib deflection of the Hybrid III dummy was 27 to 60% of the applied stroke.
2) Under rib loading, the ribs contralateral to the side of loading in the human cadaver had an A-P delfection of 0 to 14% of the applied stroke, and in the Hybrid III dummy 9 to 31 % of the applied stroke.
3) Under sternal loading, the posterior ribs of the cadavers deflected less than 5% of the applied stroke and in the dummy 8 to 10%.

CONCLUSIONS

In conclusion, the human cadaveric thorax is much more compliant than that of the Hybrid III under quasi-static loading. It is assumed that much of this is due to the difference in material properties of the ribs of the human skeleton vs. the Hybrid III. It is also hypothesized that the material properties of the costal cartilage contribute greatly to the less stiff response seen in the human cadaver. Preliminary finite element analysis by a graduate student Shijie Ruan of a two-dimensional closed hoop acting as a compression ring with a 4" length of cartilagenous tissue inserted on either side of the sternum decreased the stiffness from 20.2 N/mm to 3.1 N/mm when compared to a closed hoop with bone material properties at the costal cartilage location. The lack of a cartilaginous rib material in the Hybrid III anterior chest wall probably contributes to the stiffer response and more uniform rib deflection seen in the Hybrid III.

REFERENCES

1. Tsitlik JE, Weisfeldt ML, Chandra N, Effron MB, Halperin HR, Levin HR: Elastic properties of the human chest during cardiopulmonary resuscitation. Critical Care Medicine 11:685-692, 1983.

ACKNOWLEDGEMENTS

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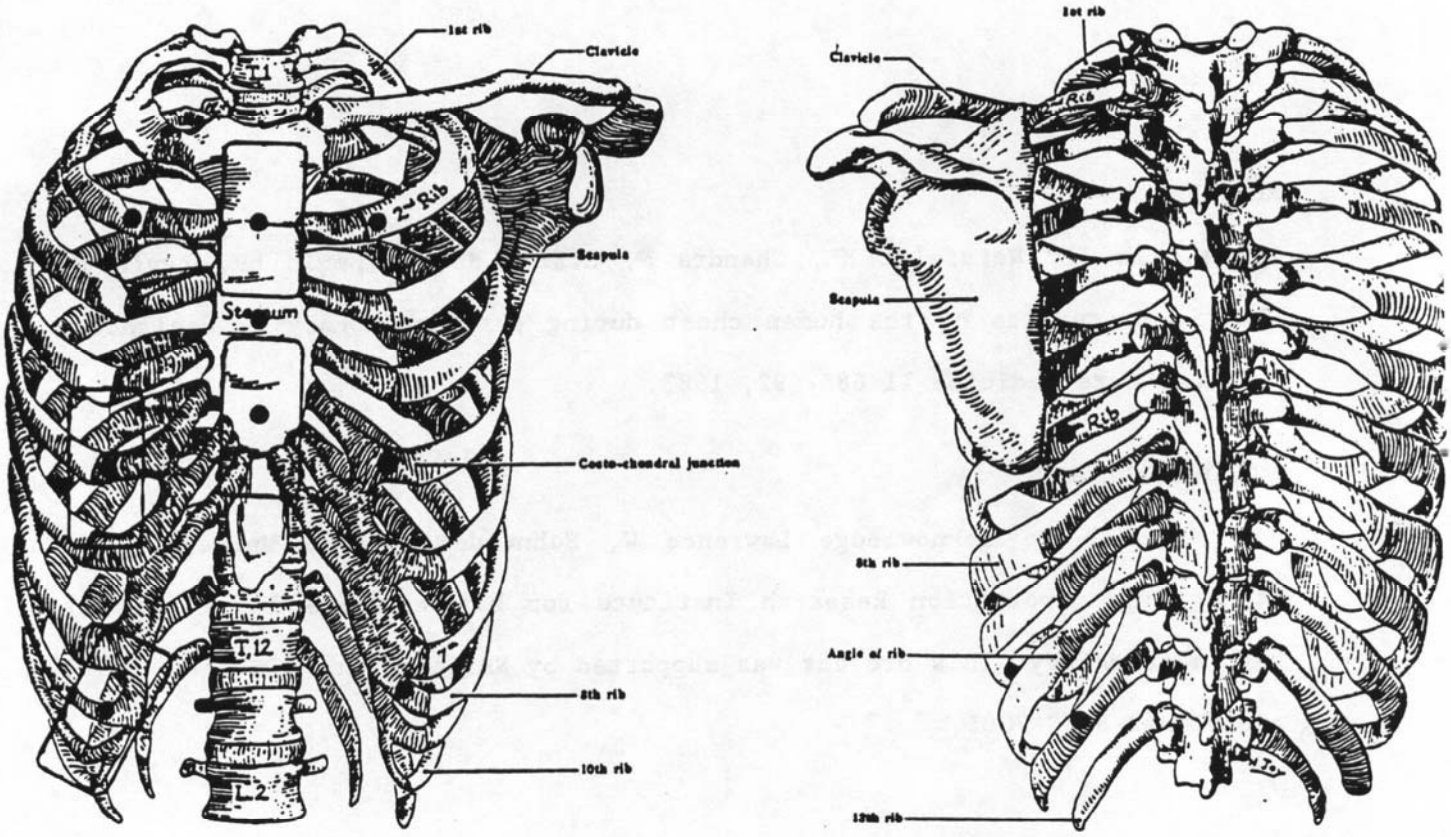


Figure 1A. Load locations (rectangles), and potentiometer locations (dots) as used in the cadaveric chest compression tests. The sternum was also loaded at mid-sternum (rectangle not shown for clarity).

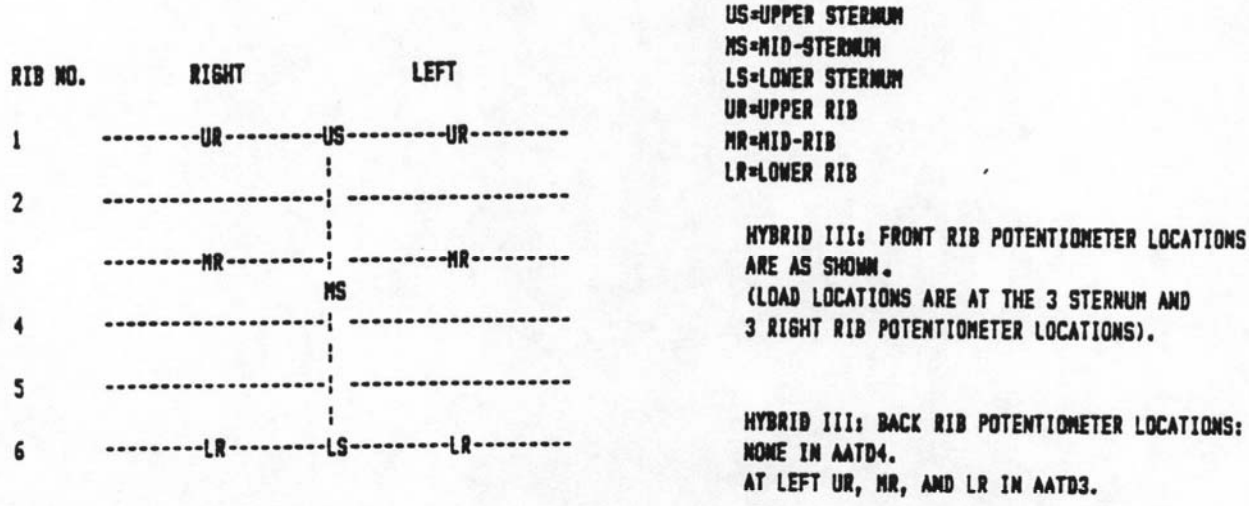


Fig. 1B. The Hybrid III load and potentiometer locations were similar: first, third and sixth ribs and upper, middle, and lower sternum.

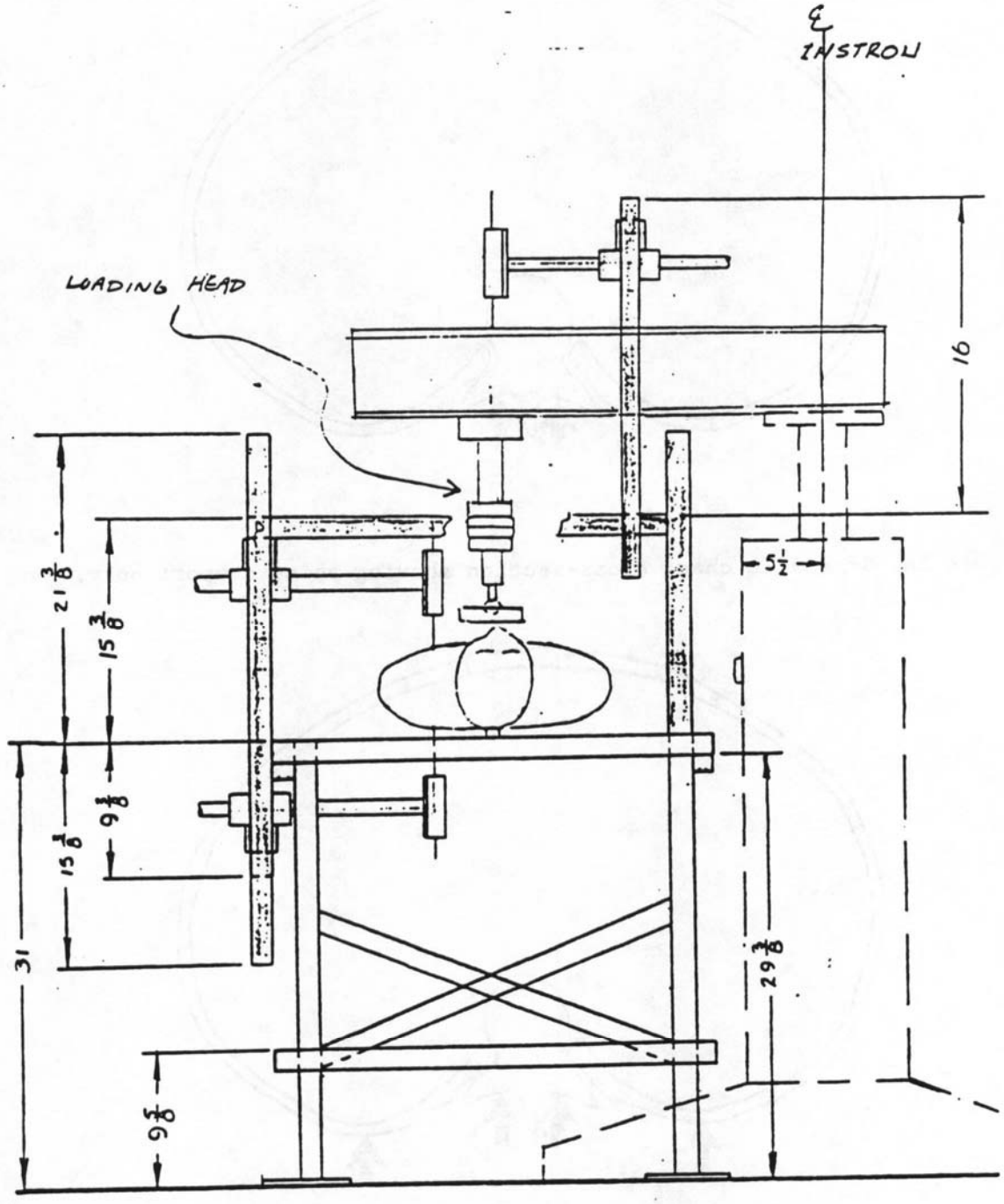


Figure 2. Unistrut support frame, Instron testing machine, and loading head.

(Dimensions in inches)

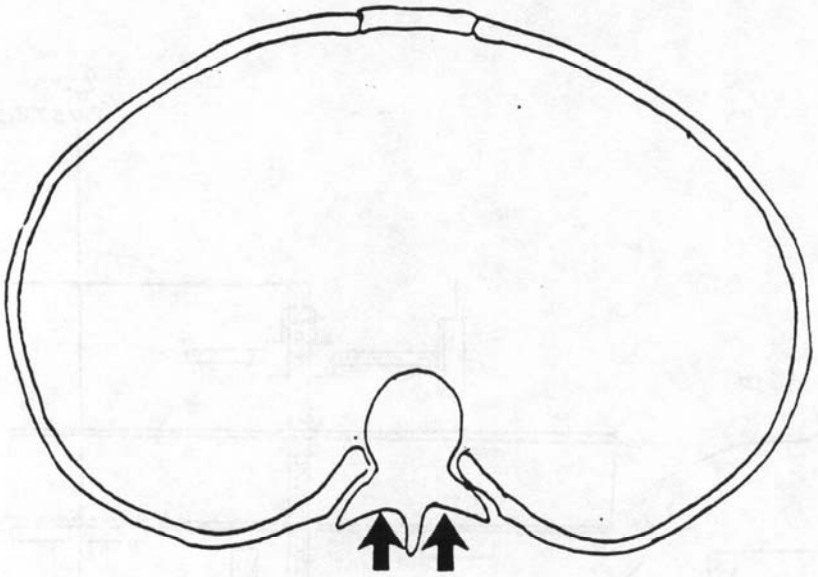


Figure 3A. Schematic chest cross-section showing spine support only.

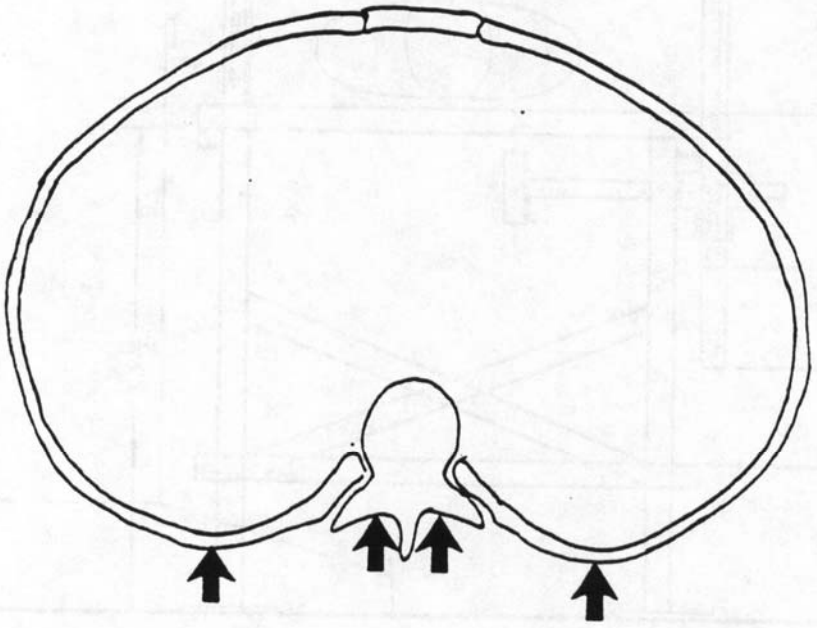


Figure 3B. Schematic chest cross-section showing rib plus spine support.

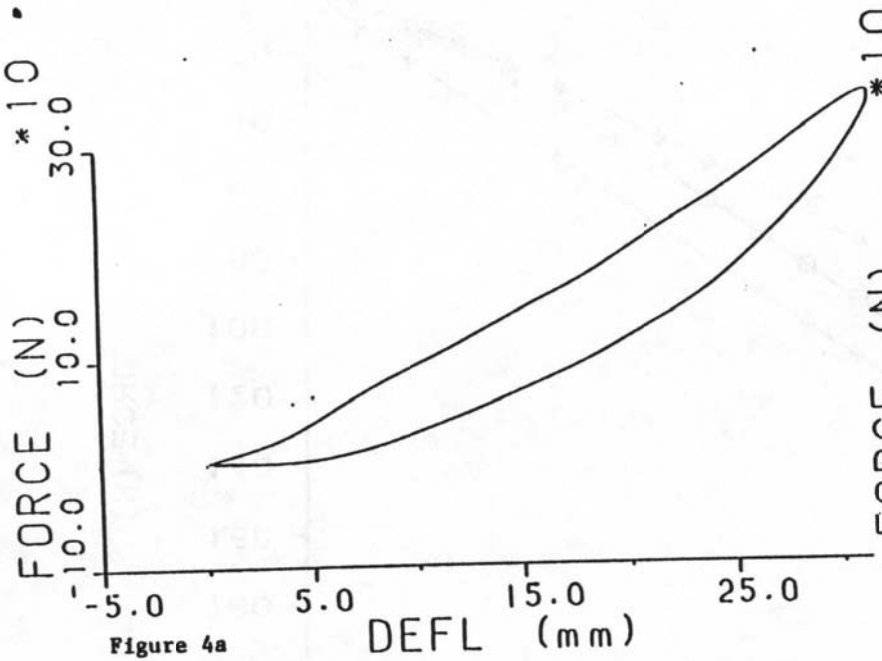


Figure 4a

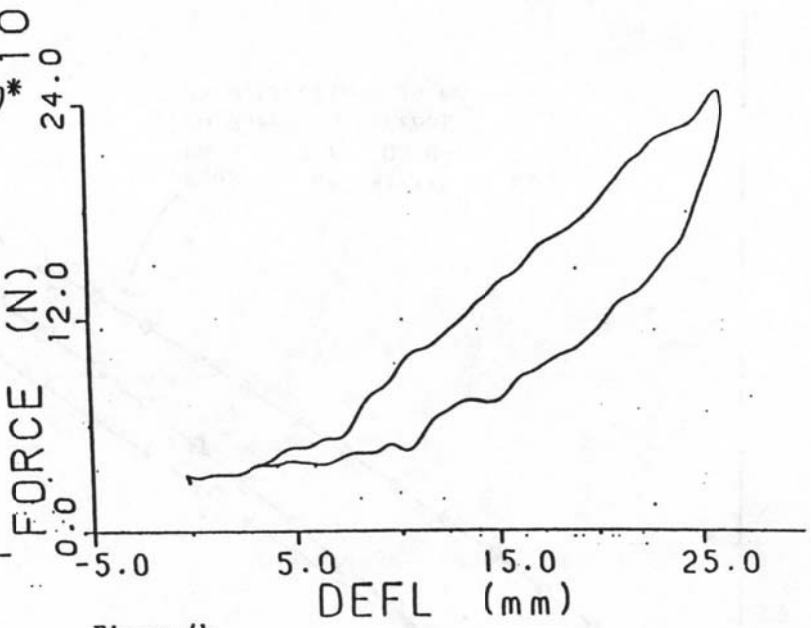
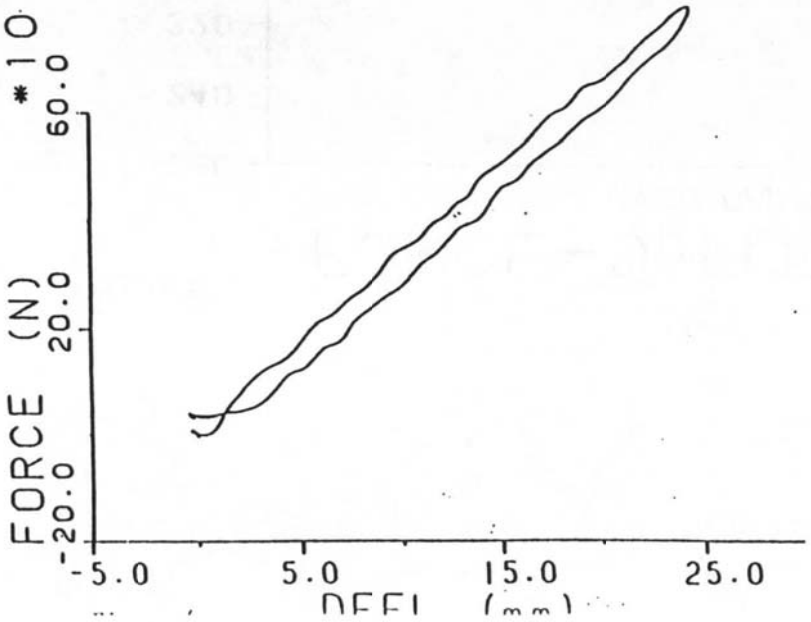


Figure 4b



Figures 4A, 4B, and 4C. Mid-sternal force-deflection curves of two cadaver runs and one Hybrid III run. 4A. Force-deflection curve of AATD2, Run #4 (Cad. #986). Max Fz - 345.0 N, max deflection - 31.3 mm 4B.Force-deflection curve of AATD5, Run #1A (Cad. #115). Max Fz - 247.7 N, max deflection - 26.1 mm. 4C. Force-deflection curve of AATD3, Run #2 (Hybrid III). Max Fz - 794.0 N, max deflection - 24.26 mm.

Figure 5

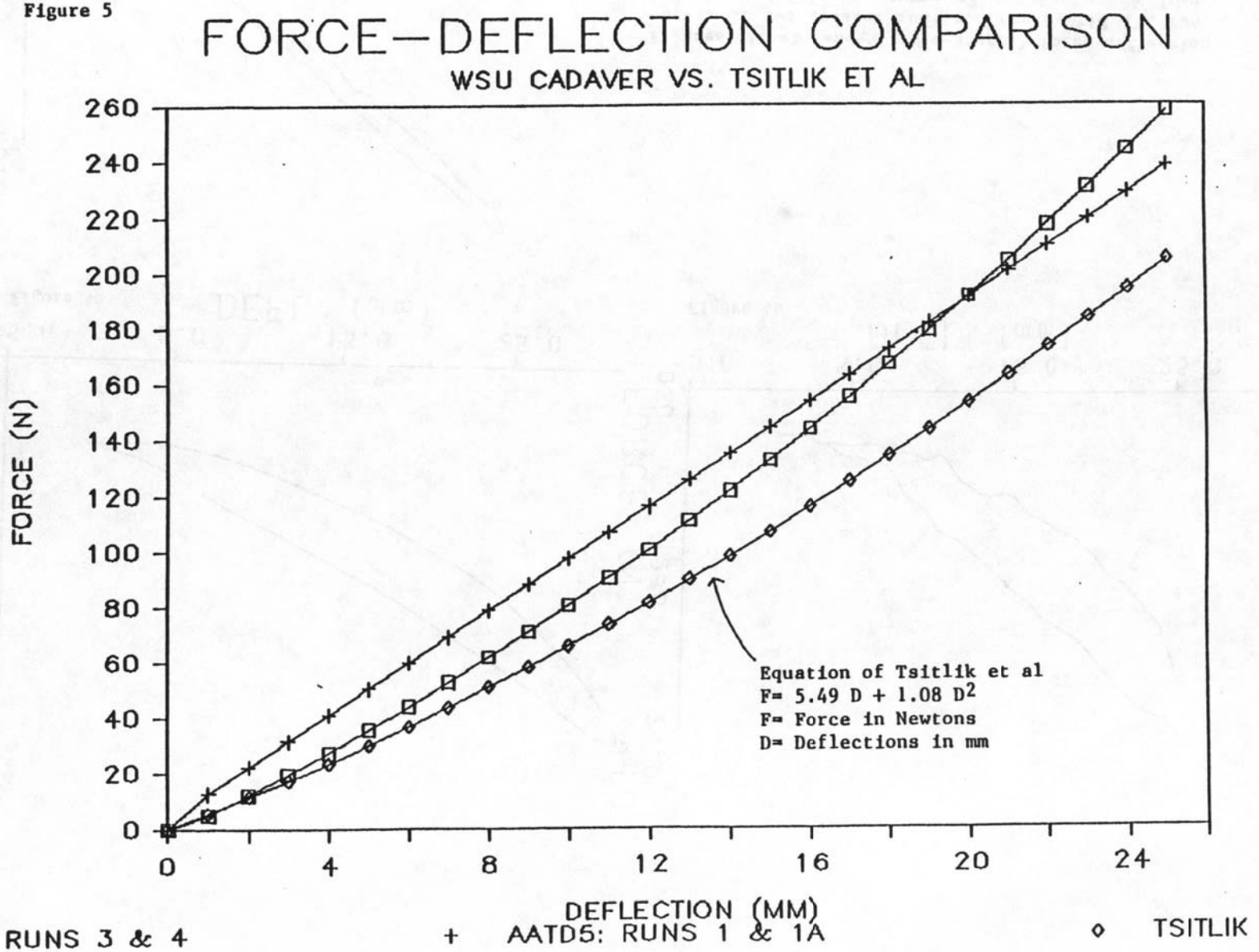

FORCE—DEFLECTION COMPARISON
WSU CADAVER VS. TSITLIK ET AL
FORCE (N)
260
240
220
200
180
160
140
120
100
80
60
40
20
0
0
4
8
12
16
20
24
DEFLECTION (MM)
Equation of Tsitlik et al
F= 5.49 D + 1.08 D2
F= Force in Newtons
D= Deflections in mm
RUNS 3 & 4
+ AATD5: RUNS 1 & 1A
◇ TSITLIK

TABLE 2

THORACIC STIFFNESS FOR CADAVER TESTS AATD2 & AATD5

	US1 0.067		MS1 0.067		LS1 0.067	
TEST NAME	AATD2 & 5	AATD5	AATD2 & 5	AATD5	AATD5	AATD5
RUN NO.	2:5,6 5:5,5A	11	2:3,4 5:1,1A	R13*	7	15
SUBJECT	CAD 986 &115	CAD 115	CAD 115	CAD 115	CAD 115	CAD 115
BACK RIB SUPPORT?	NO	YES	NO	YES	NO	YES
MAX. FORCE (N)	230.59	278.11	247.96	275.10	192.78	152.47
MAX DEFL. (MM)	25.17	24.51	25.36	25.91	25.00	26.04
STIFFNESS (N/MM)	9.16	11.35	9.78	10.62	7.71	5.86

	US1 4.0		MS1 4.0		LS1 4.0	
TEST NAME	AATD5	AATD5	AATD5	AATD5	AATD5	AATD5
RUN NO.	6	12	2,2A	14	8	16
SUBJECT	CAD 115	CAD 115	CAD 115	CAD 115	CAD 115	CAD 115
BACK RIB SUPPORT?	NO	YES	NO	YES	NO	YES
MAX. FORCE (N)	182.50	267.78	212.16	207.91	157.51	154.95
MAX DEFL. (MM)	24.73	24.77	24.67	25.68	25.02	26.22
STIFFNESS (N/MM)	7.38	10.81	8.60	8.10	6.30	5.91

	UR1 0.067	UR1 4.0	MR1 0.067	MR1 4.0	LR1 0.067	LR1 4.0
TEST NAME	AATD5	AATD5	AATD5	AATD5	AATD5	AATD5
RUN NO.	25	26	21	22	17	18
SUBJECT	CAD 115	CAD 115	CAD 115	CAD 115	CAD 115	CAD 115
BACK RIB SUPPORT?	YES	YES	YES	YES	YES	YES
MAX. FORCE (N)	147.79	152.63	136.67	136.26	89.01	93.42
MAX DEFL. (MM)	26.25	26.20	25.36	25.57	26.00	26.04
STIFFNESS (N/MM)	5.63	5.83	5.39	5.33	3.42	3.59

*R13: MAX FORCE SHOWN FOR R13 HAS BEEN INCREASED BY
(AVG MAX FORCE IN RUNS 1,1A)/(MAX FORCE IN RUN R1).
RUNS 1 & 1A WERE BEFORE RIB FRACTURE; R1 & R13 WERE AFTER RIB FRACTURE.

UR=UPPER RIB
MR=MID RIB
LR=LOWER RIB

CODE:
US1 0.067=UPPER STERNUM LOADED TO 1" STROKE AT A RATE OF 0.067"/S
US1 4.0 =UP ER STERNUM OADED TO 1" STROKE AT A RATE OF 4.0 "/S
ETC.

TABLE 3

THORACIC STIFFNESS FOR HYBRID III TESTS AATD3 & AATD4

	US1 0.067		MS1 0.067		LS1 0.067	
TEST NAME	AATD3	AATD4	AATD3	AATD4	AATD3	AATD4
RUN NO.	6	11	2	7	10	15
SUBJECT	HYB III	HYB III	HYB III	HYB III	HYB III	HYB III
BACK RIB SUPPORT?	NO	YES	NO	YES	NO	YES
MAX. FORCE (N)	685.28	735.28	794.00	874.08	688.25	668.16
MAX DEFL. (MM)	25.40	25.40	25.40	25.40	25.40	25.40
STIFFNESS (N/MM)	26.98	28.95	31.26	34.41	27.10	26.31

	US1 4.0		MS1 4.0		LS1 4.0	
TEST NAME	AATD3	AATD4	AATD3	AATD4	AATD3	AATD4
RUN NO.	7	12	4	8	12	16
SUBJECT	HYB III	HYB III	HYB III	HYB III	HYB III	HYB III
BACK RIB SUPPORT?	NO	YES	NO	YES	NO	YES
MAX. FORCE (N)	807.87	897.57	1004.85	1125.38	765.24	844.27
MAX DEFL. (MM)	25.40	25.40	25.40	25.40	25.40	25.40
STIFFNESS (N/MM)	31.81	35.34	39.56	44.31	30.13	33.24

	UR1 0.067	UR1 4.0	MR1 0.067	MR1 4.0	LR1 0.067	LR1 4.0
TEST NAME	AATD4	AATD4	AATD4	AATD4	AATD4	AATD4
RUN NO.	3	4	1	2	5	6
SUBJECT	HYB.III	HYB.III	HYB.III	HYB.III	HYB.III	HYB.III
BACK RIB SUPPORT?	YES	YES	YES	YES	YES	YES
MAX. FORCE (N)	805.60	831.54	1426.94	1863.06	1124.50	1504.48
MAX DEFL. (MM)	25.40	25.40	25.40	25.40	25.40	25.40
STIFFNESS (N/MM)	31.72	32.74	56.18	73.35	44.27	59.23

US=UPPER STERNUM UR=UPPER RIB
MS=MID STERNUM MR=MID RIB
LS=LOWER STERNUM LR=LOWER RIB

CODE:
US1 0.067=UPPER STERNUM LOADED TO 1" STROKE AT A RATE OF 0.067"/S
US1 4.0 =UPPER STERNUM LOADED TO 1" STROKE AT A RATE OF 4.0 "/S
ETC.

TABLE 4

THORACIC DEFORMATION FOR CADAVER TEST AATD5

STERNUM LOADING.
LOADING RATE: 0.067 IN/S
MAX STROKE: 1.0 INCH
SUPPORT CONDITIONS: SPINE SUPPORTED.
POSTERIOR RIBS SUPPORTED BILATERALLY.
LOAD LOCATION IS SHOWN ABOVE EACH TABLE.
DEFLECTIONS ARE SHOWN IN INCHES AT EACH LOCATION.

LOAD POINT: UPPER STERNUM
NO. CADAVERS: 1
TESTS: AATD5: 11

RIGHT RIBS	STERNUM	LEFT RIBS
2: 0.50	U: 1.00	2: 0.48
	M: ----	
5: 0.18	L: 0.35	5: 0.20
8: 0.06		8: 0.07

LOAD POINT: MID STERNUM
NO. CADAVERS: 1
TESTS: AATD5: 13

RIGHT RIBS	STERNUM	LEFT RIBS
2: ----	U: ----	2: 0.37
	M: 1.00	
5: 0.31	L: ----	5: 0.30
8: 0.18		8: 0.15

LOAD POINT: LOWER STERNUM
NO. CADAVERS: 1
TESTS: AATD5: 15

RIGHT RIBS	STERNUM	LEFT RIBS
2: 0.15	U: 0.16	2: 0.26
	M: ----	
5: 0.63	L: 1.00	5: 0.39
8: 0.57		8: 0.52

RIB LOADING.
LOADING RATE: 0.067 IN/S
MAX STROKE: 1.0 INCH
SUPPORT CONDITIONS: SPINE SUPPORTED.
POSTERIOR RIBS SUPPORTED BILATERALLY.
LOAD LOCATION IS SHOWN ABOVE EACH TABLE.
DEFLECTIONS ARE SHOWN IN INCHES AT EACH LOCATION.

LOAD POINT: RIGHT 2ND RIB
NO. CADAVERS: 1
TESTS: AATD5: 25

RIGHT RIBS	STERNUM	LEFT RIBS
2: 1.00	U: 0.31	2: 0.13
	M: ----	
5: 0.22	L: 0.24	5: 0.00
8: 0.05		8: 0.01

LOAD POINT: RIGHT 5TH RIB
NO. CADAVERS: 1
TESTS: AATD5: 21

RIGHT RIBS	STERNUM	LEFT RIBS
2: 0.08	U: 0.04	2: 0.01
	M: ----	
5: 1.00	L: 0.49	5: 0.09
8: 0.40		8: 0.12

LOAD POINT: RIGHT 8TH RIB
NO. CADAVERS: 1
TESTS: AATD5: 17

RIGHT RIBS	STERNUM	LEFT RIBS
2: 0.00	U: 0.00	2: 0.00
	M: ----	
5: 0.42	L: 0.42	5: 0.11
8: 1.00		8: 0.14

TABLE 5

THORACIC DEFORMATION FOR HYBRID III TEST AATD4

STERNUM LOADING.
LOADING RATE: 0.067 IN/S
MAX STROKE: 1.0 INCH
SUPPORT CONDITIONS: SPINE SUPPORTED.
POSTERIOR RIBS SUPPORTED BILATERALLY.
LOAD LOCATION IS SHOWN ABOVE EACH TABLE.
DEFLECTIONS ARE SHOWN IN INCHES AT EACH LOCATION.

LOAD POINT: UPPER STERNUM
HYBRID III
TESTS: AATD4: 11

RIGHT RIBS	STERNUM	LEFT RIBS
1: 0.58	U: 1.0	1: 0.60
3: 0.44		3: 0.48
6: 0.32	L: 0.52	6: 0.34

LOAD POINT: MID STERNUM
HYBRID III
TESTS: AATD4: 7

RIGHT RIBS	STERNUM	LEFT RIBS
1: 0.56		1: 0.58
3: 0.54	M: 1.0	3: 0.55
6: 0.53		6: 0.59

LOAD POINT: LOWER STERNUM
HYBRID III
TESTS: AATD4: 15

RIGHT RIBS	STERNUM	LEFT RIBS
1: 0.27	U: 0.41	1: 0.31
3: 0.34		3: 0.38
6: 0.47	L: 1.0	6: 0.53

RIB LOADING.
LOADING RATE: 0.067 IN/S
MAX STROKE: 1.0 INCH
SUPPORT CONDITIONS: SPINE SUPPORTED.
POSTERIOR RIBS SUPPORTED BILATERALLY.
LOAD LOCATION IS SHOWN ABOVE EACH TABLE.
DEFLECTIONS ARE SHOWN IN INCHES AT EACH LOCATION.

LOAD POINT: RIGHT 1ST RIB
HYBRID III
TESTS: AATD4: 3

RIGHT RIBS	STERNUM	LEFT RIBS
1: 1.0	U: 0.52	1: 0.31
3: 0.50		3: 0.19
6: 0.33	L: 0.32	6: 0.09

LOAD POINT: RIGHT 3RD RIB
HYBRID III
TESTS: AATD4: 7

RIGHT RIBS	STERNUM	LEFT RIBS
1: 0.80	U: 0.67	1: 0.29
3: 1.0		3: 0.24
6: 0.74	L: 0.68	6: 0.25

LOAD POINT: RIGHT 6TH RIB
HYBRID III
TESTS: AATD4: 5

RIGHT RIBS	STERNUM	LEFT RIBS
1: 0.43	U: 0.33	1: 0.10
3: 0.56		3: 0.15
6: 1.0	L: 0.67	6: 0.26

DISCUSSION

PAPER: Quasi-Static Frontal Loading to the Thorax of Cadavers and Hybrid III Dummy

SPEAKER: J.M. Cavanaugh, Wayne State University

Q: Ted Kennedy, Consulting Engineer

I don't think you determined during your testing, but is it conceivable, with an air bag for loading in the frontal area, to get rib fractures in the back without any in the front? You have good distribution of the loading in the front, and actually flex the ribs.

A: Cavanaugh

I haven't been involved in any dynamic pendulum type tests but I don't think they showed posterior rib fractures. Maybe somebody else could verify that?

A: Guy Nusholtz, Chrysler

I've seen fractures in the back very near the spine with impacts to the front. But normally you also have fractures in the front as well, and you have to hit them fairly severely.

Q: Guy Nusholtz, Chrysler

You showed a curve where you said the response was nonlinear. Did perhaps part of the cadaver yield or fracture and that was the result. Did you check that?

A: With one inch strokes we didn't get rib fracture. During strokes we heard rib fracture and verified that with autopsy. I think for these cases which were one inch, it wasn't due to fracture.

Q: It could have been some hysteresis not related to a fracture phenomenon? It looked pretty linear when it went straight out. It didn't seem to show any indication of yielding.

A: Well there were two up there I didn't really concentrate too much on the first one. The first one was more nonlinear than the second one. The second order curve is pretty flat; comparable to what has been seen in live volunteers.

Q: Are you attributing nonlinearity to the fact that it doesn't come back down the rise line? It looked like a straight line to me. It looked linear on the rise and then it had a hysteresis coming back.

A: We ran a linear and nonlinear fit through the rising portion

of the curve and a nonlinear fit better. The linear fit was still close. The correlation coefficient was quite good for the linear fit but quite a bit better for the nonlinear fit. For the unloading portion, which we haven't checked, I think a third order equation looks like it might fit the unloading portion better than the second order equation.